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DEVELOPMENT AND APPLICATION OF A FAST-RUNNING TOOL TO CHARACTERIZE SHOCK DAMAGE WITHIN TUNNEL STRUCTURES

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Abstract

Successful but time-intensive use of high-fidelity computational capabilities for shock loading events and resultant effects on and within enclosed structures, e.g., tunnels, has led to an interest in developing more expedient methods of analysis. While several tools are currently available for the general study of the failure of structures under dynamic shock loads at a distance, presented are a pair of statistics- and physics-based tools that can be used to differentiate different types of damage (e.g., breach versus yield) as well as quantify the amount of damage within tunnels for loads close-in and with standoff. Use of such faster running tools allows for scoping and planning of more detailed model and test analysis and provides a way to address parametric sensitivity over a large multivariate space.

Introduction

High fidelity computational hydrodynamic and structural analysis tools, e.g., the ALE3D, DYNA3D and CTH codes (Sharp, 2004; Lin, 2005; McGlaun et al., 1990), are useful for predicting the response of structures to shock loads (see Figure 1) and can ultimately be used to assist vulnerability corrective measures and reduce overall risk (e.g., Noble et al., 2008; Glascoe et al., 2009; McMichael et al., 2009). Unfortunately, such tools require significant computational resources which can undermine timely assessment involving a large range of threats and threat locations. In addition, high fidelity tools are typically deterministic in nature and, therefore, must assume a specified set of material properties for the structure itself. Large uncertainties associated with, for example, material strength need to be at least bounded for a proper risk assessment. Consequently, there is a need for capabilities that can rapidly evaluate effects associated with various threat sizes, threat locations, and system states while quickly highlighting uncertainties associated with structural and system response.

This paper presents two components of a proposed fast-running tool for confined spaces such as tunnels. The first component is a physics-based approach for predicting shock propagation in tunnels that runs in minutes on a standard single processor platform. This capability can be used to rapidly determine the spectrum of loading environments associated with the range of credible threats, threat locations and tunnel networks. The second component is a statistical treatment for predicting and bounding close-in structural response at varying standoff using previously executed high fidelity loading realizations.

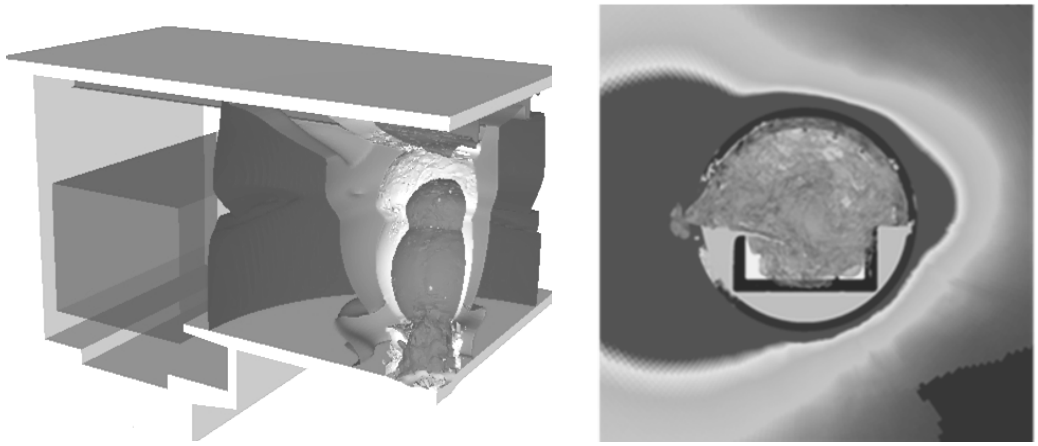

Figure 1: Two examples of high fidelity ALE3D simulation of a blast within enclosed tunnel structures. The plot on the left illustrates different pressure contours after a shock within an enclosed station, the plot on the right highlights a fully-coupled three-dimensional fluid/structure/soil blast simulation.

A Fast-running Tool for Blasts in Tunnels: the STUN code

Direct simulation of blast propagation in tunnels is a formidable task due to a combination of factors. Firstly, flow in long tunnels is dominated by boundary layer effects, such as wall drag, that require high resolution zoning. Tunnels, by nature, have high length over diameter ratios, resulting in highly protracted computational domains relative to tunnel diameter. Such long domains, coupled with high resolution requirements needed to capture boundary effects, makes direct three-dimensional simulation of long tunnels prohibitively expensive. Even two-dimensional simulations of extensive tunnel lengths become computationally expensive when considering multiparameteric study. The sphere and tunnel code (STUN) employs a simpler algorithm that captures the essential physics of blasts in tunnels (Glenn, 2001), but runs in minutes on standard personal computing hardware. STUN is based on an algorithm originally developed for the study of hypervelocity launchers and gas guns (e.g., Glenn, 1990 and 1997) and is, in part, based on the one-dimensional wall drag model:

$$\frac{du}{dt} + \frac{1}{\rho}\frac{\partial p}{\partial x} + \frac{f}{4r}u|u| = 0$$

where u is the particle velocity in the x direction, ρ is the air density, p is pressure in the tunnel, A is the cross-sectional area of a tunnel of radius r, and the friction coefficient, $F = f/4r$. The friction factor, f, the Prandtl-Karman "Law of the Wall", is a function of the Reynolds number:

$$f^{-1/2} = 2\log_{10}\left(\mathrm{Re} f^{1/2}\right) - 0.8$$

The STUN code works by coupling several one-dimensional representations of the tunnel and blast into a higher dimensional representation. Specifically, STUN includes a spherical flow region for the detonation that is coupled to an axial one-dimensional model of tunnel segments. By varying the cross section of the tunnel along its length, it is possible to account for the effect of platforms (larger cross section) and trains (restricted cross section) upon the blast wave propagation and attenuation. The code can predict the effect of an arbitrary number of bends in a tunnel and supports coupling to additional 1-D segments to simulate the effect of tunnel intersections upon the shock wave. STUN incorporates treatments for blast doors displaceable and potentially fragmented by dynamic loading.

STUN has been validated against several sets of data involving a range of threat sizes and tunnel configurations. Consider results from a specific experiment involving blast loading on a single straight tunnel section containing two doors (see Figure 2). This particular test configuration has a relatively low length to diameter ratio allowing response prediction with high fidelity codes in two-dimensions. For this example high fidelity CTH simulations were exercised for comparison. Figure 3 illustrates consistency between experiment and the two numerical solutions and demonstrates that STUN results can track experimental results better than the higher fidelity CTH results at the first gauge.

The addition of an intersection, or bend in the tunnel makes this example inherently three-dimensional and far more expensive for a high-fidelity code to execute. In sharp contrast, the cost of the corresponding STUN calculation is minimal. Such a fast-running tool is ideally suited for providing pressure histories at a distance along a complex tunnel/station configuration to examine, for example, down-tunnel blast effects on personnel or impulse loading of structural components.

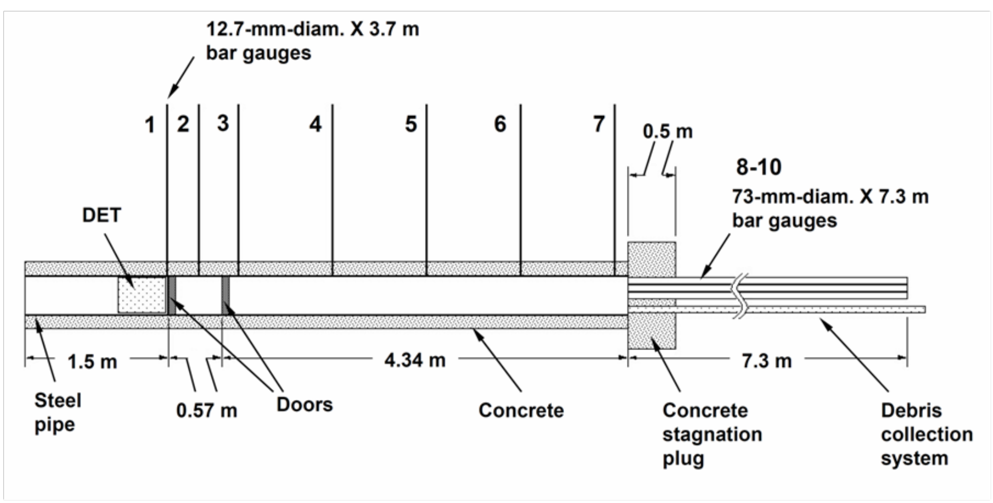

Figure 2: Experimental configuration with <u>D</u>ilute <u>E</u>xplosive <u>T</u>ile placed against blast door outside a single, straight tunnel.

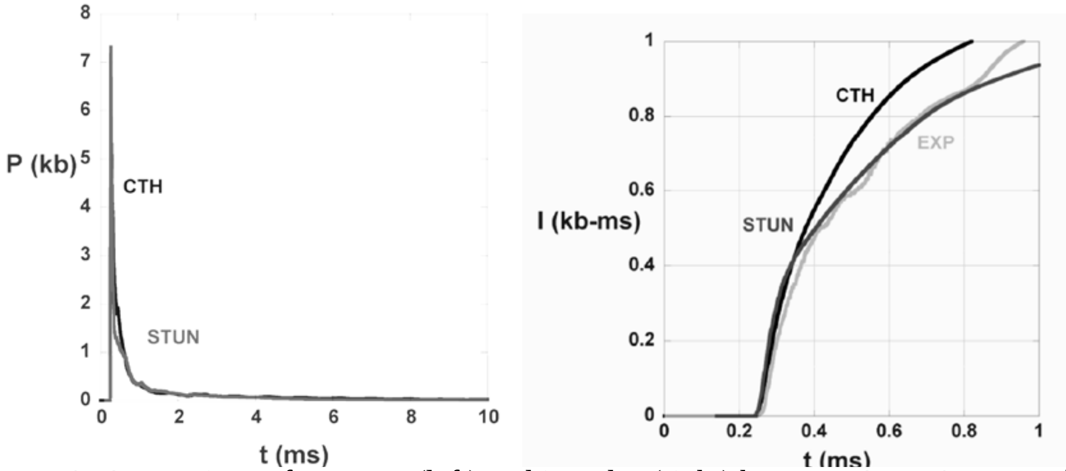

Figure 3: Comparison of pressure (left) and impulse (right) between CTH, STUN and experimental result at the location of gauge #1.

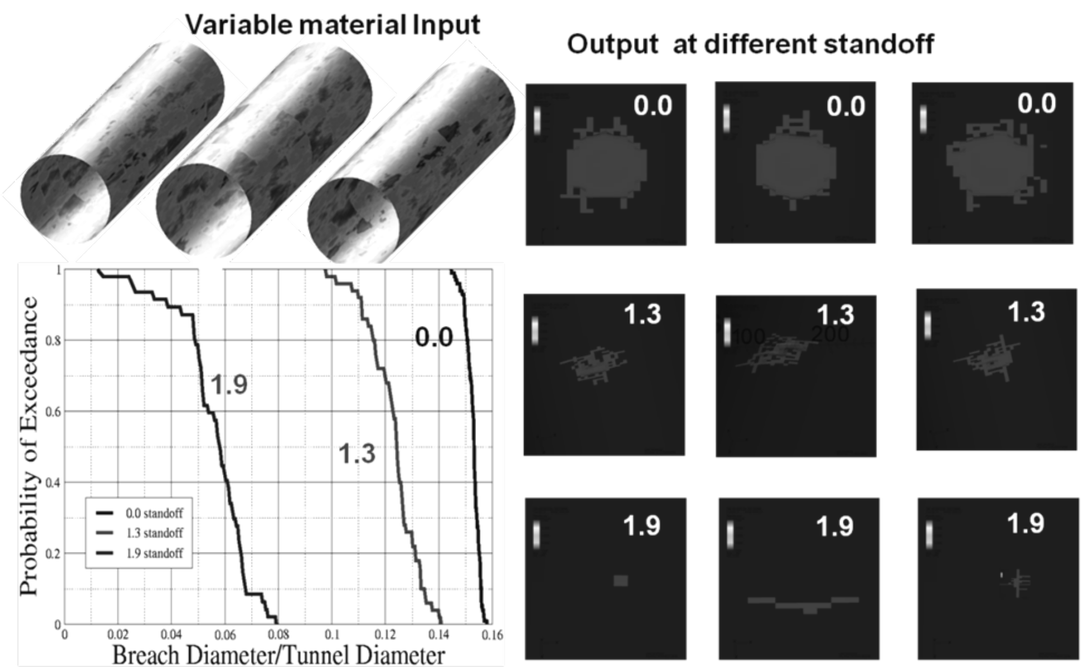

Figure 4. Three stochastic realizations (top left three tunnels with spatially varying material strength) of breach failure for three stand-off distances (right close-ups of breach hole at standoff 0.0, 1.3 and 1.9); based upon the results over hundreds of high fidelity 3-D finite element realizations.

Fast-running Failure Assessment with Uncertainty Quantification

Analysis of close-in structural response within confined tunnel environments to idealized explosive blast scenarios is an inherently difficult three-dimensional problem (Figure 1). Accounting for uncertainty requires more than a single deterministic simulation and can greatly benefit from faster running techniques. The tradeoff, of course, is that simplifications associated with faster-running techniques can introduce additional uncertainty. Under carefully considered conditions, trends gleaned from high fidelity 3D analysis and experiments can be used to generalize response curves. Such easily referenced curves may include the effect of uncertainties when cast in a probabilistic framework (Koutsourelakis et al., 2006). Uncertainty associated with, for example, material properties throughout a given structure can be incorporated into assessments to highlight probabilities of failure under specific threat conditions (Figure 4).

Generalized but structurally detailed 3D scenarios can be considered to address tunnel types based on construction (e.g., 3/8” steel shell structures versus 3’ thick reinforced concrete structures) at different threat size and standoff configurations. Each scenario can account for uncertain parameters associated with considerations affecting the defined tunnel type, such as material strength or local geologic conditions. Advanced regression techniques can utilize and then inform on computationally demanding 3D finite element simulations of these tunnel scenarios by sampling model output over a multivariate space (e.g., Mardia et al., 1979). For example, a statistical approach comprising a logistic and a regular regression could evaluate damage to a specific tunnel structure in terms of engineering plastic strain (EPS) and the area exceeding a predefined threshold of EPS as a function of threat size and standoff. Specifically, the dependence of a subset of the finite element output, such as strain damage and damaged area, on a part of its input, such as threat weight and distance, is fit to a two-step regression:

- Step 1: logistic regression on the whole data set for two categories: “no breach” and “breach”.
- Step 2: Regular regression for the part of the set with non-zero values of maximum EPS.

The variables in the regression models include finite element input along with the corresponding output of maximum EPS and the size of the yield area for different EPS thresholds. To analyze how different failure modes depend on the range of inputs, a failure criterion needs definition, such as ‘a breach occurs when plastic yielding exceeds a specified threshold, and the size of the related area exceeds a specified value’. In statistical terms, this definition is a binary response, Z, which is “1” when breach occurs, and “0” otherwise. Breach is analyzed as a function of covariates (threat size and standoff) using a logistic regression model. Specifically, logistic regression relates the probability of breach to the covariates, X_i, as follows:

$$\log\left(\frac{p_i}{1-p_i}\right) = X_i^T\beta + \epsilon, \quad i = 1, \ldots, n$$

where $p_i = \Pr(Z_i = 1|X_i)$ and n is the number of data points.

In addition to the binary breach mode, another finite element output is the damage area, Y, that is a positive number wherever there is a breach, otherwise $Y = 0$. For a subset m of n data points for which the failure $Z_i = 1$, area $Y_i \geq y_{threshold}$, and maxEPS $\geq max\mathrm{EPS}_{threshold}$, a second stage to the statistical model can be added,

$$\log(Y_i) = X_i^T \gamma + \delta, \quad i = 1, \ldots, m$$

Fitting the compound regression model provides estimates of coefficients, β and γ, along with the corresponding error bounds. Fitted values are in turn used in a simulation to calculate predictive distributions of the probability of breach and distributions of breach size at a desired set of values for threat weight and distance.

As an example, consider a study with 94 three-dimensional finite element realizations for two tunnel structures similar to that pictured on the right in Figure 1: a strengthened tunnel breaching at a high strain, and a weakened tunnel breaching at a low strain. The logistic response curve is generated using the approach described on breached (solid points) and non-breached (open points) realizations; this is plotted as a function of threat size versus standoff in Figure 5. Figure 6 illustrates the second stage fit of the standard regression on extent of damage as a function of threat size (shown for three standoff values). Figure 7 highlights the role of uncertainty captured by the regression fit with 99% confidence intervals banding the damage area versus threat size (shown at 10 inches standoff).

This statistical model is only a first and demonstrative step in quickly characterizing response and uncertainty associated with detailed high-fidelity simulation. It can be thought of as a statistical approximation of the finite element model for a given set of inputs and outputs. Such a statistical model can provide both qualitative and quantitative insight into the input/output dependencies of interest and associated uncertainties. Improved statistical approximation and improved efficiency of assembly of finite element input may be attained using informed sampling techniques such as Latin Hypercube or Sequential Importance Sampling (e.g., pp. 227-246 of Doucet et al., 2001) to reduce the number of realizations necessary to generate the response curves.

Conclusions

Fast-running tools can be used to predict blast effects within confined structures in a timely manner allowing for uncertainty assessment. Two different approaches to building a fast-running capability have been discussed: a one-dimensional physics-based pressure propagation tool and a statistical treatment of high fidelity effects analysis. The former provides rapid theory-based analysis of blast effects within a confined structure at a distance; the latter is useful for estimates of close-in structural integrity at a specific location accommodating some degree of uncertainty and is entirely based on previously examined high fidelity deterministic analysis. The combination of these capabilities into a single integrated model can provide engineers and decision-makers with a tool allowing timely analysis when considering shock loading events within confined environments, such as tunnel structures.

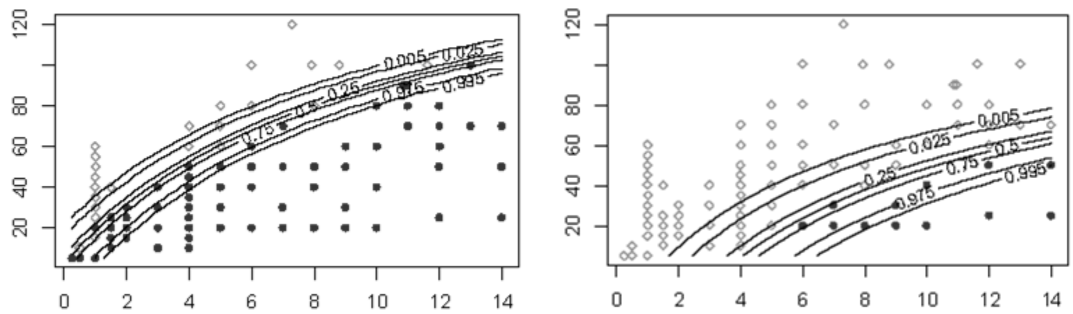

Figure 5. Response curves of **threat size vs standoff** for a strengthened structure (left) and a weakened structure (right) where solid points indicate breached realizations and open circles indicate nonbreached realizations.

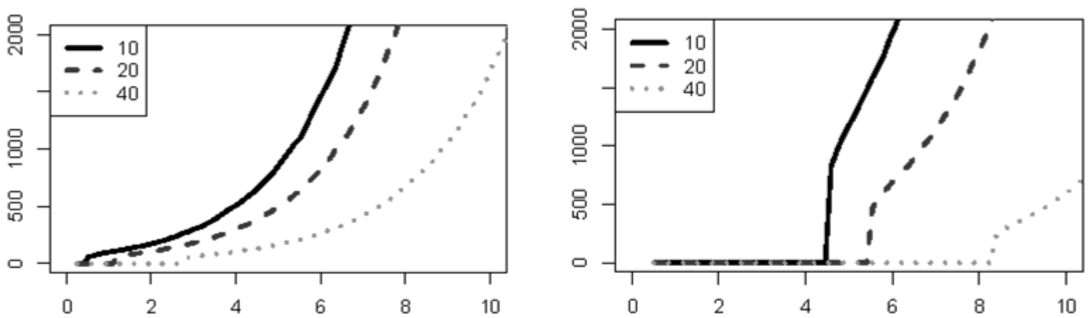

Figure 6. Reponse curves of **breached area as a function of threat size** for a strengthened structure (left) and a weakened structure (right) for three standoff distances (10 inches, 20 inches, and 40 inches).

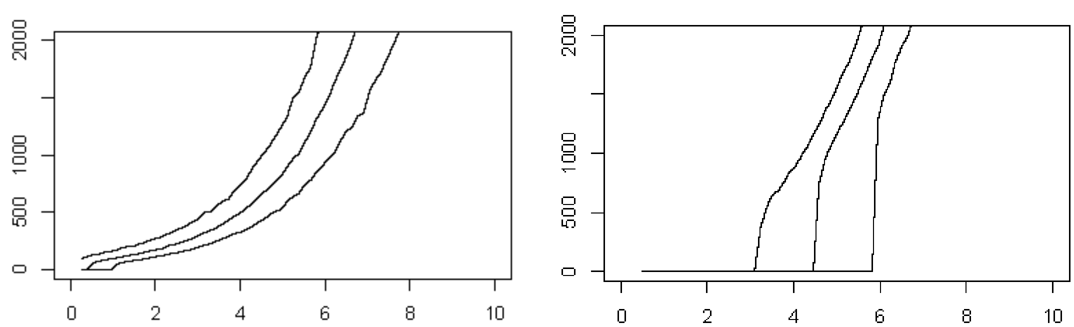

Figure 7. Pointwise 99% confidence intervals for **breached area versus threat size** for a strengthened tunnel (left) and a weakened tunnel (right) at 10 inches standoff. The three curves indicate the mean and the 99% pointwise confidence interval for each response fit.

Acknowledgements

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